Revolutionary Propulsion Research

Presentation to
National Research Council
Independent Review of the
Pioneering Revolutionary Technologies Program

June 12-17, 2002

Revolutionary Propulsion Research Project

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    - Advanced Sails and Interstellar Propulsion
    - Systems Analyses of Advanced Concepts
    - Breakthrough Propulsion Physics
    - Other

Revolutionary Propulsion Research Project: Organization and Management Structure

- **Project Office**
  - Under Advanced Space Transportation Program Office at MSFC
  - Manager, John Cole
  - Deputy Manager, Ron Litchford

- **NASA Center Task Managers**
  - ARC – Unmeel Mehta
  - GRC – Craig Williams, Mark Millis (BPP)
  - JPL – Ira Katz, Jay Polk
  - MSFC – Jim Martin, Steve Rodgers

Revolutionary Propulsion Research Project

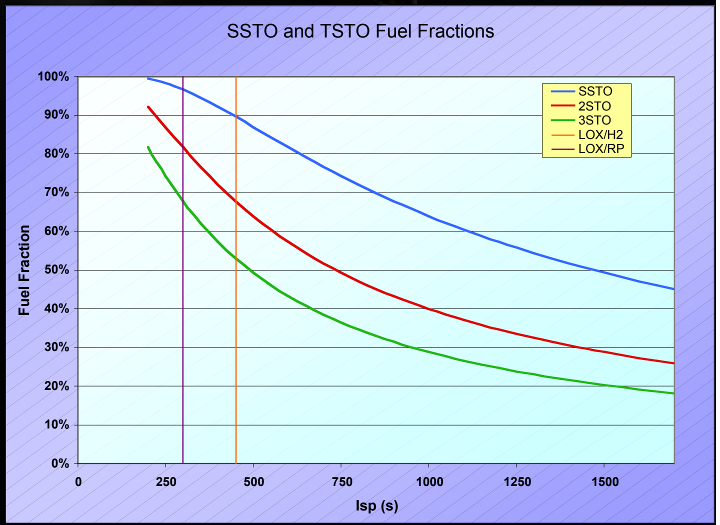
- **Goals & Objectives**
  - Look beyond current space transportation architectures and produce the science that might lead to low fuel fraction, low cost, revolutionary space access vehicles
  - Contribute to fundamental advancement of in-space propulsion technologies that can ultimately enable short-duration, on-demand travel to any location in the solar system, as well as penetration of the interstellar medium
  - Demonstrate scientific proof-of-principle of extremely energetic and enabling propulsion technologies
  - Work closely with STLT/3rd Gen and In-Space programs as well as NEXT (NASA Exploration Team) to transfer and promote emerging propulsion technologies when appropriate
  - Promote a culture of "*excellence in research*" – Demand Good Science

- **Focus Area is Highly Energetic Propulsion**
  - High Specific Energy/Power
    - highly energetic reactions / off-board resources / ultra energy storage & power conversion
  - High Temperatures & Electromagnetics
    - plasma sciences / high temperature technologies / plasma accelerators / MHD
  - Non-Chemical Energy Sources
    - fission, fusion, antimatter, nuclear isomers
  - Continued Support of Advanced Chemical Research
    - high energy density fuels / advanced cycles

Why is Propulsion Energetics Research Needed?

♦ Earth Orbit Access Technical Challenges

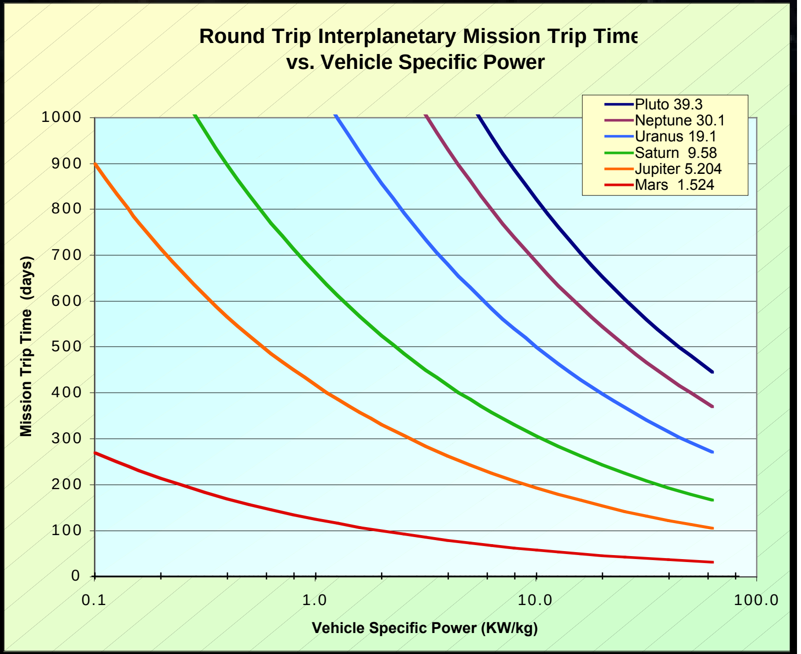
- The fundamental technical obstacles to routine space access are related to two basic parameters of <u>Energetics</u>
  - Specific Energy (reducing fuel fraction requires higher Isp)
  - Specific Power (T/W > 1 requires multi-GW power)
- Routine space access operations will ultimately require propulsion systems possessing robust performance margins
  - Adding features such as wings, landing gear, contingency fuel, operability, safety requirements, and more payload demands higher specific impulse (desired fuel fraction < 70%)
  - Order of magnitude increase in Isp with 1< T/W < 3
  - Implies order of magnitude increase in vehicle specific energy without sacrificing specific power



- Currently, <u>No Technologies Exist</u> that can significantly reduce fuel fraction while providing the specific energy/power needed to place a given mass in orbit
- <u>Research Avenues Do Exist</u>, however, that may enable the desired specific energy
  - High energy density propellants
  - Beamed energy from ground based power sources
  - Closed cycle nuclear systems (safe, very high specific power)
  - Ultra-high-density energy storage
- Research Avenues also exist for developing engines with the required specific power
  - Electromagnetic thrust augmentation, for example

Why is Propulsion Energetics Research Needed?

- **In-Space Transportation Challenges**
  - The fundamental technical obstacles to deep space (beyond mars) transportation are also related to propulsion energetics
    - Specific Energy
      - low IMLEO demands high Isp propulsion
    - Specific Power
      - short trip times demand high Δv maneuvers (i.e., high jet power for high acceleration)
  - Affordable, short-duration, on-demand travel beyond mars will require robust performance margins
    - Order of magnitude increase in specific energy
      - delivered mass fraction > 50%
    - Specific Power ~ 10 kW/kg
      - outer-planet round trips measured in days rather than years



… must break through 1 kW/kg barrier and ultimately approach ~ 10 kW/kg

  - Requirements far beyond our current plans for Nuclear Electric Propulsion (~0.03 KW/kg)
  - Potential research avenues
    - Advanced closed-cycle nuclear electric propulsion best near-term prospect
    - Fusion and antimatter good long-term prospects
    - Beamed energy and sails may help
    - Component research also needed (high-temperature radiators / flight-weight magnets)
    - Breakthrough propulsion physics (new scientific discoveries)

Rationale for Propulsion Energetics Research

- **Push technology to enable commercial ventures and space voyages that are not currently feasible**
  - Propulsion is the key limiting factor in most "over the horizon" missions, such as:
    - Safe, low-cost, routine earth-to-orbit transportation
    - Rapid, safe, and affordable transportation of large payloads throughout the solar system
    - Penetration of the interstellar medium and timely return of scientific information
- **Propulsion energetics appears to be best plausible research strategy**
  - A strategic investment for advancing beyond today's planned space transportation technologies
  - NASA must make this investment, since there is no **current** commercial incentive or military need for this capability
  - Potential solutions are neither quick nor simple
  - Need to start developing the scientific underpinnings now rather than later

Research Investment Categories

- Advanced Chemical
- Electromagnetics & Plasma-Based
- Advanced Nuclear (Fission, Fusion, & Antimatter)
- Advanced Sails and Interstellar Propulsion
- Systems Analysis
- Breakthrough Propulsion Physics

Propulsion Research Approach for 2003

- **Budget Split, preliminary**

	FY03	FY04
– Assume a budget of, after taxes	$6895 K	$6916 K
– Allocated for NRA's		
• Breakthrough Propulsion Physics	650 K	650 K
• Propulsion Research	2000 K	2000 K
– Allocated for In-House	4245 K	4266 K
• JPL	1100 K	same
• GRC	1000 K	
• MSFC	1245 K	
• ARC	350 K	
• Project Management	550 K	
– 8 FTE for PO and managing NRA contracts	400 K	
– Workshops	50 K	
– Graphics Support	30 K	
– Other	70 K	

Programmatics

- **Programmatic Approach**
  - Demonstrate scientific feasibility and, if possible, mature technologies to TRL 3
  - Encourage widest possible dissemination of scientific results
  - Enhance and develop NASA in-house capabilities
    - To perform world-class scientific research
    - To effectively manage advanced propulsion research activities across the agency
  - Utilize unique external expertise and facilities (avoid duplication of existing capability)
    - DoD/DOE Laboratories (contracts & support of IPA's)
    - Universities (primarily grants)
    - Private Sector (contracts & SBIR's)
  - Stimulate education and extend graduate research opportunities
  - Release NRA's directed at selected emphasis areas – as funding permits

Investment Strategy

- **Investment Strategy**
  - 50% of funds distributed broadly in relatively small efforts
  - 50% of funds invested in three "focus areas"
  - NRA's released when budget permits
    - e.g., NRA 8-17 (launch assist / pulse detonation engines)
    - Unable to release NRA during past few years (insufficient funds)
    - Preferred approach for focus areas
  - Selection criteria for in-house and external tasks.
    - Research addresses revolutionary propulsion and satisfies the project objectives
    - Research is reviewed and endorsed by appropriate management advisory team
    - Involves a low cost meaningful experiment
    - Provide some results each year and conclusive findings within 5 years
    - Constrained by available resources
  - A few unsolicited proposals have been selected (< 1 in 10)
  - Some augmented SBIR's and University grants
- **Customers**
  - Space Transportation and Launch Technology (Code R)
  - In-Space Transportation (Code S)
  - NEXT - NASA Exploration Team (Code M)

Management Strategy

- **Progress Evaluation / Assuring Technical Excellence**
  - Virtually all tasks are funded at level-of-effort ($ and manpower)
  - Research progress depends on many intangible (non-quantitative) factors
    - Capability & enthusiasm of investigators
    - Leveraging of resources and expertise
    - Adequate resources and time for maturation of ideas
  - Task Planning & Review Cycle
    - Identify critical (make or break) issues at an early stage and focus research efforts
    - Stress proof-of-concept experiments (establish *scientific feasibility*)
    - Set realizable schedule/milestones consistent with budget constraints
    - Require annual publication of research results (deliverable)
    - Annual review cycle by appropriate NASA Task Managers
    - Graduate, continue, or terminate decision annually
      - Terminate for non-performance or technologically unfeasible (negative findings)
      - Anticipate 10 - 20 % annual washout (use freed funds to pick up new work)
    - However, should avoid punishing researchers for good science that leads to negative findings
    - Continual dialogue with customers

Investment Portfolio: Focus Areas

Emphasis on a few selected research areas leading to high-payoff propulsion technologies

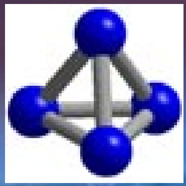
- **Magnetohydrodynamics (MHD)**
  - MHD Augmented Propulsion Experiment (MSFC/LyTec)
  - MHD-Bypass Hypersonic Airbreathing Engine (ARC)
  - MHD Slipstream Accelerator (RPI)
  - High Power Nuclear MHD Space Propulsion (INSPI/University of Florida)
- **Fusion**
  - Magnetic Nozzle Simulator for Fusion Plasma Conditions (GRC/OSU)
  - Coaxial Helicity Injection Experiment (GRC/Princeton University)
  - Magnetized Target Fusion (MSFC/LANL)
  - Magnetic Nozzle Technology for Pulsed Micro-Fusion (MSFC)
- **High Power (MW-Class) Electric Thrusters for Deep Space NEP**
  - 500 kW Lithium-Fed Lorentz Force Accelerator (JPL)
  - 1 MW Bismuth Anode Layer Thruster (JPL)
  - 1-MW Ion Engine Feasibility (JPL)
  - FRC Thruster (MSFC/ University of Washington)

Summary of Investment Portfolio

♦ Advanced Chemical

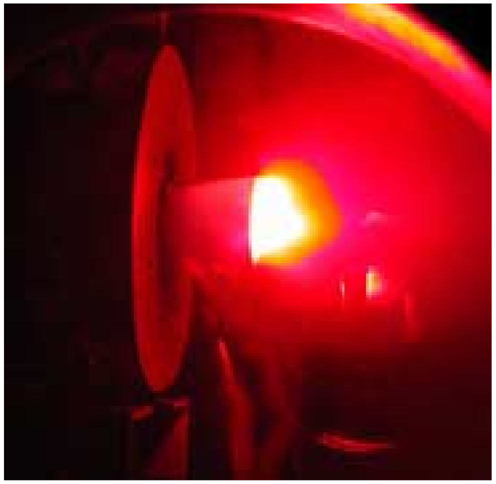
– Realities of Chemical Propulsion
  - Will never provide ultimate desired capabilities
  - All we have for now and for some time to come
  - Some performance improvements possible
– High Energy Density Fuels
  - Advanced hydrocarbons (AFRL/MSFC)
    – ΔIsp = 20 sec / specific gravity = 1.1
    – AFRL-Edwards provided MSFC with several advanced hydrocarbon fuels
    – Initial screening of these fuels completed in 2001
  - Recombination energy fuels (GRC)
    – High risk monopropellant (Isp =550 - 700 sec)
    – Experiments on formation of solid hydrogen snow completed in 2001
    – Video-based analysis of particle formation and design of next phase of experiment during 2002
  - Metallic Hydrogen (Harvard University)
    – Analysis of metallic hydrogen existence at megabar pressures
  - Td N4, Tetrahedral Nitrogen (ARC)
    – Synthesis paths explored using numerical chemistry in 2001
    – Negotiations with AFRL to attempt synthesis (difficulties with low funds)
– Many other promising fuels and cycles can no longer be pursued at this time

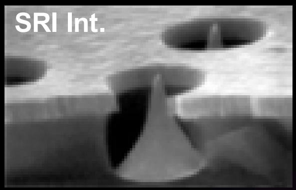
Solid molecular hydrogen particles (H2 matrix) formed on the surface of the liquid helium (circled)



Summary of Investment Portfolio

- **Electromagnetics / Plasma Based**
  - Electromagnetics is a path for bypassing thermal limits
    - Aim is conversion of electromagnetic energy to momentum
    - Mainly oriented toward plasma based concepts
  - Megawatt-Class Electric Thrusters (JPL)
    - Li-fueled LFA test facility constructed
    - 500 KW LFA thruster in assembly (initial testing in 2002)
    - Contract with TsNIIMASH to design a subscale 200 kWe-class bismuth anode layer thruster
    - 1 Megawatt ion engine design feasibility assessment underway
    - Several field emitter concepts built and tested in 2001 and 2002 (tests ongoing)





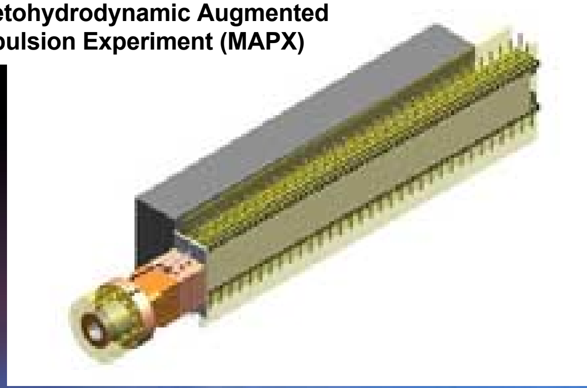
Lithium-Fed Lorentz Force Accelerator

Summary of Investment Portfolio

- **Electromagnetics / Plasma Based (cont'd)**
  - MHD Accelerators (ARC/MSFC/LyTec/AFRL)
    - Small-scale MHD accelerator built and in-test at Ames Electric Arc Shock Tunnel
      - to support MHD bypass hypersonic engine research
    - 1 MW steady flow MHD accelerator experiment using 1-MW arcjet driver at MSFC
      - support electrically augmented rocket research
      - analysis and design complete / fabrication and assembly ongoing
    - Planning continues for development of a 20-MW accelerator experiment at ARC
    - MHD slipstream accelerator experiment at RPI
    - Development of comprehensive CFD code for high-temperature plasma/MHD flows (ARC/Stanford/MSFC)

ARC MHD Accelerator Assembly

Magnetohydrodynamic Augmented Propulsion Experiment (MAPX)



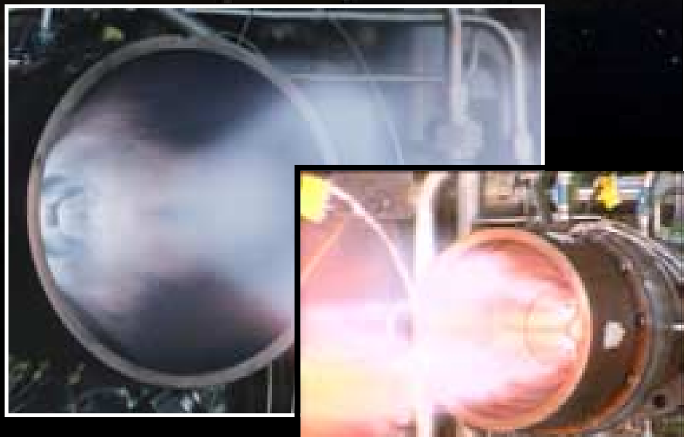
MHD Slipstream Accelerator

Summary of Investment Portfolio

- **Electromagnetics / Plasma Based (cont'd)**
  - Beamed Energy
    - Microwave Lightcraft rectenna testing at Renssalear Polytechnic Institute
    - Laser Lightcraft CFD analyses at MSFC in support of AFRL-Edwards research
  - Flight Weight Magnets
    - High-purity aluminum magnet completed and tested in 2001 by LSU
    - Development of low-weight superconductor magnet flux pump continues at LSU
  - MagLev Launch Assist
    - Army and PRT conducting flywheel and drone launch studies into 2002

Summary of Investment Portfolio

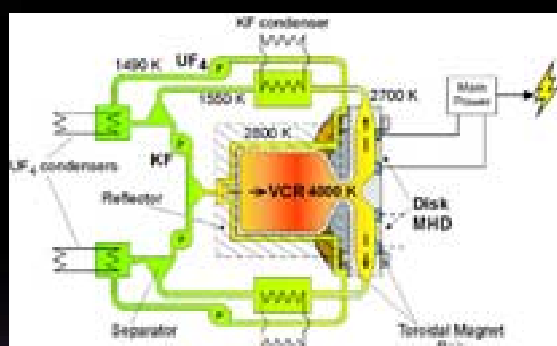
- **Nuclear - Advanced Fission**
  - Chemical systems already pushed to limit
  - Nuclear offers a new growth path
    - Potential for 10^6 factor of improvement in specific energy
    - Best near-term prospect (relatively high TRL)
    - Potential to achieve specific power > 1 kW/kg with high-temperature reactor
    - Would also like to start exploring possible utilization of isomers as funding levels permit
  - LOX Augmented NTR
    - First series of LOX injection testing of simulated NTR completed by GRC in 2001
    - Planning and experiment design for next series of tests will continue into 2002
  - High Temperature Nuclear Fuels
    - Effort focuses on cermet and carbide fuels potentially capable of enabling high performance (>0.1 kW/kg) nuclear electric propulsion system as well as nuclear thermal rockets with mission averaged specific impulse >850 secs
    - Significant progress made by INSPI/ University of Florida in fuel characterization and fabrication methodologies (effort continuing into 2002)

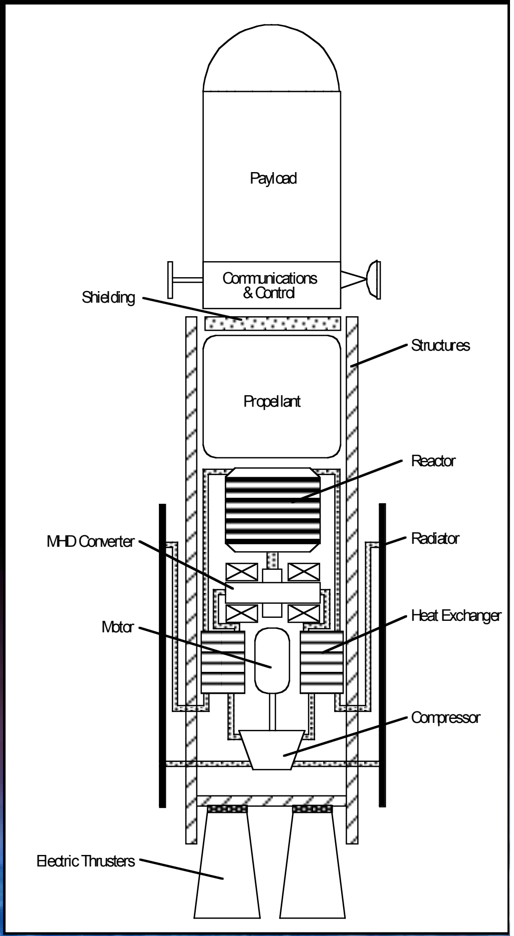


Aerojet Corp Test Rig
LANTR hot fire test
(25:1 area ratio)

Summary of Investment Portfolio

- **Nuclear - Advanced Fission (cont'd)**
  - Nuclear Electric MHD Systems (Psp > 1 KW/kg)
    - University of Florida analysis and assessment of vapor core reactor with MHD energy conversion for deep space NEP is continuing
    - Neutron ionization enhancement experiment at MSFC temporarily halted (lack of adequate resources)
      - Fundamental data obtained using electron gun to simulate neutron flux
      - Planned research includes in-pile experimentation to confirm predictions based on modeling and electron-gun results
      - May be able to restart research through an NRA solicitation



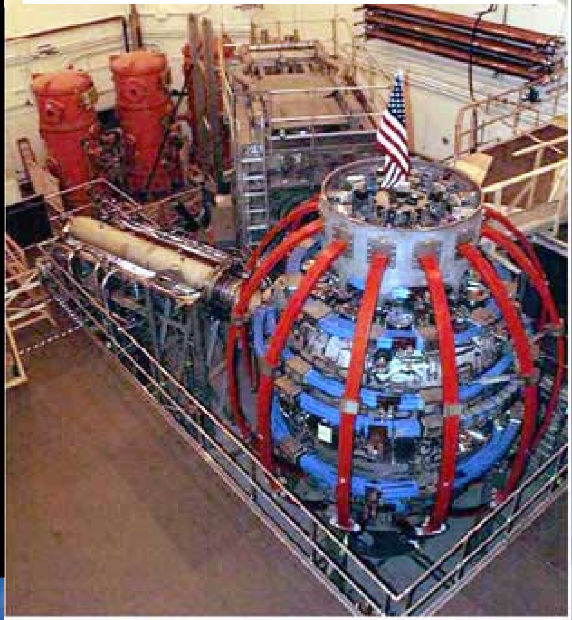


Summary of Investment Portfolio

♦ Nuclear - Fusion

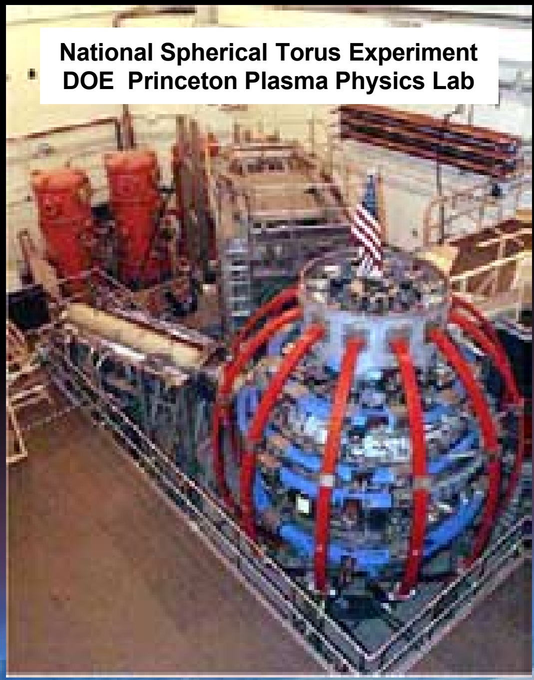
- Very high energy density reactions
  - Theoretical Isp ≈ 10^6 sec
    (with low neutron yield reactions)
  - Benefits from energy conversion process inside the plasma
  - May require innovative confinement schemes
- High payoff but high risk
  - Controlled fusion breakeven power never demonstrated
  - Serious research requires major fiscal investments (distraction?)
  - Envisioned systems tend to be big (high IMLEO)
- Potential benefits demand we start now
  - Payoff would be immense (~ 10 kW/kg)
  - Frontline researchers confident of success
  - DOE has made significant progress
  - NASA can pursue only with substantial DOE help

Spherical Torus Experiment



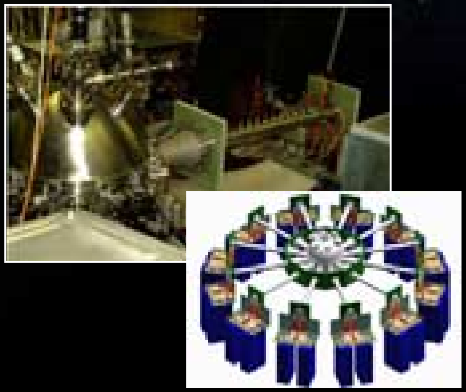
Summary of Investment Portfolio

- **Nuclear - Fusion (con't)**
  - Magnetic Nozzle Simulator (GRC/OSU)
    - Final report on plasma/propellant boundary layer
    - Coil hardware fabricated, test cell configured for test
    - Initial attempt at low power test
  - Helicity Injection (GRC/Princeton University)
    - Defined experimental campaign with NSTX research plan
    - CHE theory development and plasma modeling
    - Small reactor study (ORNL)



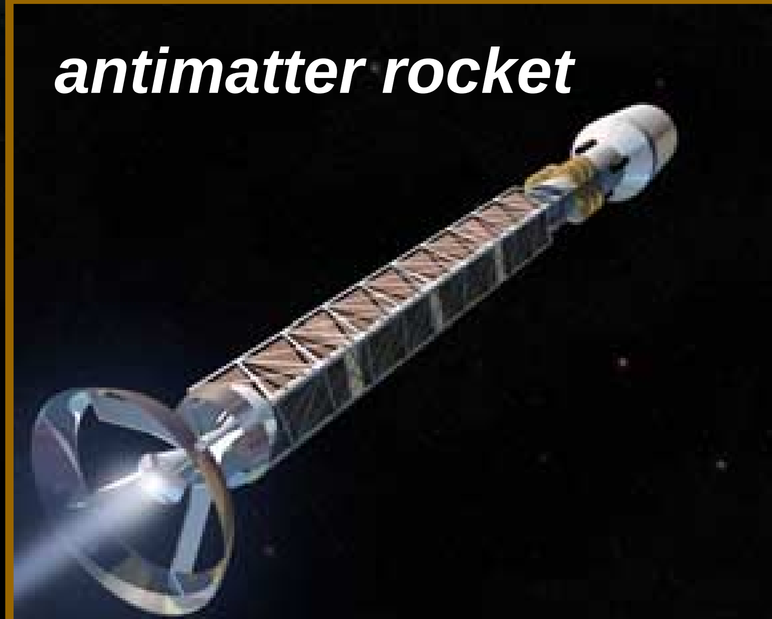
Summary of Investment Portfolio

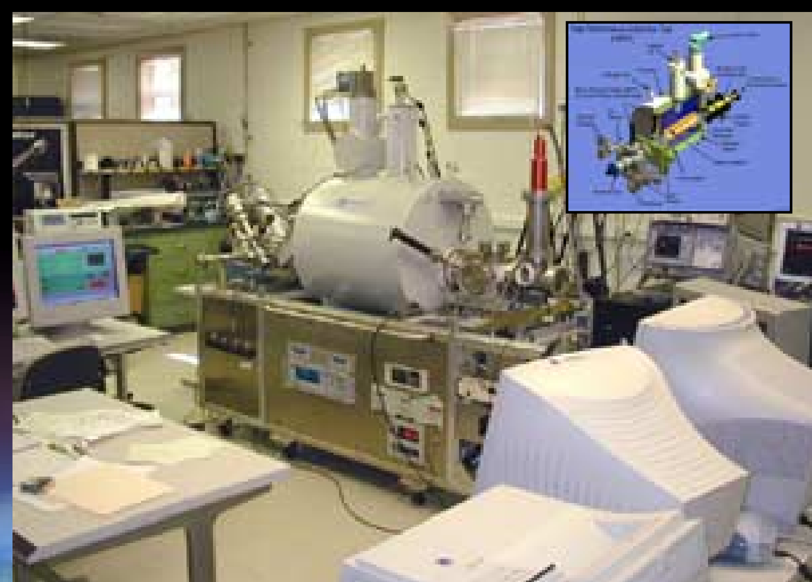
- **Nuclear - Fusion (cont'd)**
  - Magnetized Target Fusion (MSFC/LANL)
    - Completed Mark-1 Marshall gun experiment demonstrating low jitter (<10 ns) and launching of 0.2 mg plasma at 62km/s
    - Initiated design of Mark-2 gun
    - Development of 2-D MHD simulation code
    - 75% design completion for FRC target generator
  - Gas Dynamic Mirror (MSFC)
    - Brought up system and demonstrated first plasma
  - IEC Fusion Reactor (MSFC)
    - Placed into operation with deuterium plasma and demonstrated neutron production
    - Applying advanced plasma diagnostics to reveal underlying physical processes
  - University Efforts
    - Z-Pinch (U. Nevada at Reno)
    - FRC (U. Washington)
    - Computational Analysis (UAH, U. Tenn.)



Summary of Investment Portfolio

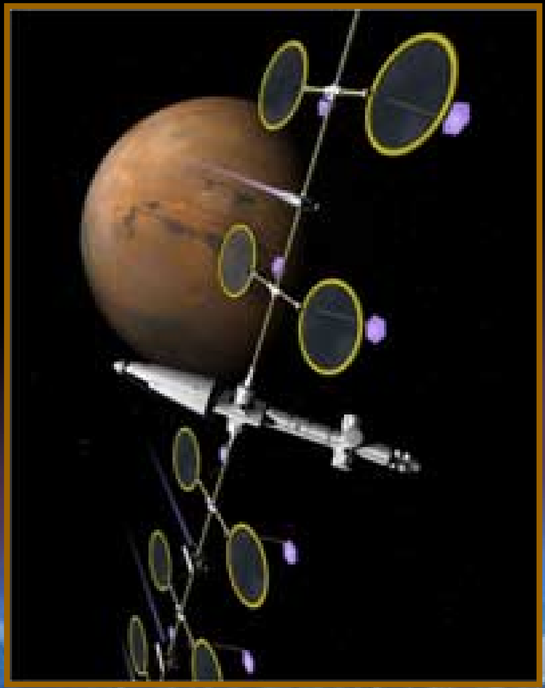
- **Nuclear - Antimatter**
  - Ultra-high energy density reaction
    - Potential for Isp > 2×10^6 sec
    - May be useful as catalyst for micro-fusion detonations as well
  - Major issues at this stage are production & storage
  - High potential for commercial spin-offs
  - Research team includes MSFC, Industry, Universities, and DOE Laboratories
- **Storage Research**
  - High Performance Antiproton Trap (HiPAT)
    - One-trillion antiproton storage capacity
    - 18-day half-life
  - Transportability
    - Fill trap at Fermi Lab
    - Transport to MSFC for utilization experiments
    - To date, only tested with normal matter
- **Antimatter Catalyzed Micro-Fusion**
  - ICAN & MICF target concepts
  - Reduce stand-off driver mass
  - Antimatter usage rate less demanding





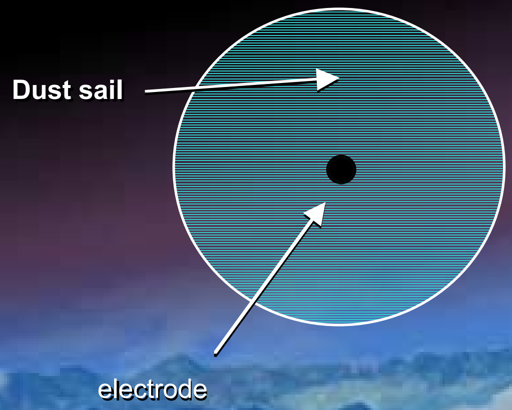
Summary of Investment Portfolio

- **Interstellar Option**
  - Specific energy requirements beyond 10^9 MJ/kg
  - May ultimately depend upon some unforeseen breakthrough
  - Limited penetration of interstellar medium is possible
    - Utilization of insitu or off-board resources
    - Solar, dust, laser, and magnetic sails
- **Other Propulsion Options**
  - Micropropulsion technology
  - Tethers
  - Very large solar electric



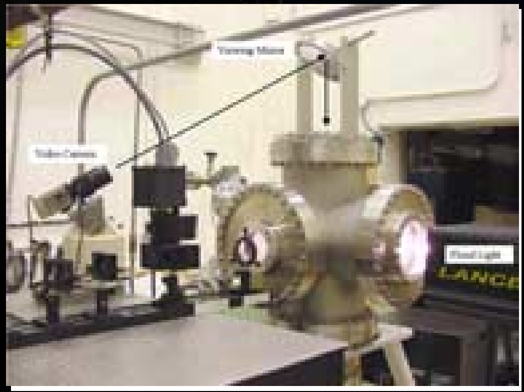
Summary of Investment Portfolio

- **Interstellar - Advanced Sails**
  - Reinforced metal film sails
    - Tasks underway include concept feasibility evaluation, bonding, film assembly, and reflectivity measurements
  - KC-135 self deploying sail experiment
    - Hoop sail experiment completed in FY01
    - Vacuum deployment tests and KC-135 tests planned for FY02
  - Electrostatic dust solar sail
    - Completed preliminary assessment of cloud coupling to spacecraft
    - Vacuum deployment test planned soon



Summary of Investment Portfolio

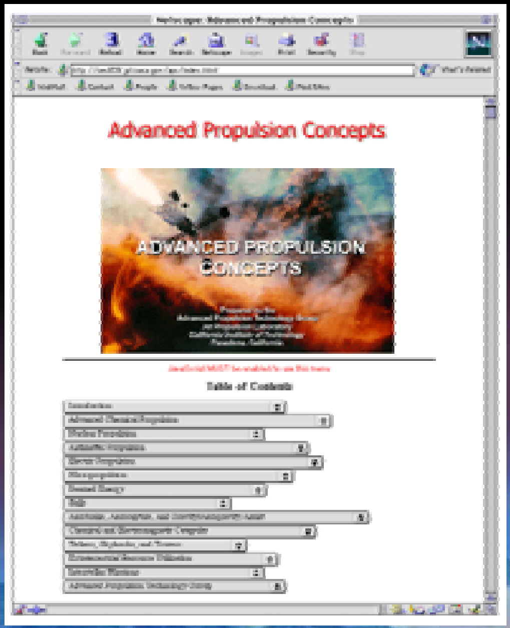
- **Interstellar - Advanced Sails (cont'd)**
  - Laser ablated sails
    - Test performed to measure coupling coefficients. Initial results in FY01
    - Final results to be presented in FY02
  - Laser sail photon measurements
    - Completed force measurements in agreement with theory to within 5%
    - Preliminary results to be presented in FY02



Summary of Investment Portfolio

- **Advanced Concepts Mission and Systems Analysis**
  - Piloted outer planet missions
    - Completed analysis of Neptune piloted mission using Multi-MW NEP
    - Completing analysis of chemical, fission, and fusion options for Neptune
  - Analysis of Jupiter and Saturn missions during FY02
  - Team X; Completed initial assessment of evolutionary approach to NEP

- **Workshop and Data Base**
  - 13th Advanced Propulsion Concepts Workshop hosted by JPL in June 2002
  - Advanced Concepts Database is being modified to ensure compatibility with ITAR guidelines



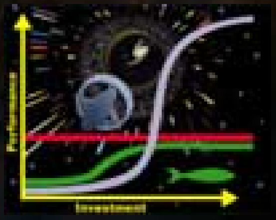
Summary of Investment Portfolio

Breakthrough Propulsion Physics (GRC)

Objectives & Goals

Objective

- **Produce advances on physics to revolutionize spaceflight and <u>enable interstellar voyages</u>**
  - Look beyond Newtonian mechanics to provide new scientific foundations for breakthrough technology.
  - Ensure that such research is conducted in credible and productive manner.



Technical Challenges (Goals)

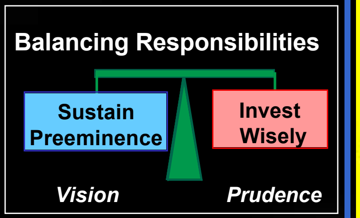
- Mass: Discover new propulsion methods that eliminate or dramatically reduce the need for propellant.
- Speed: Discover how to circumvent existing limits to dramatically reduce transit times.
- Energy: Discover new methods to power these propulsion devices.

Research Tasks

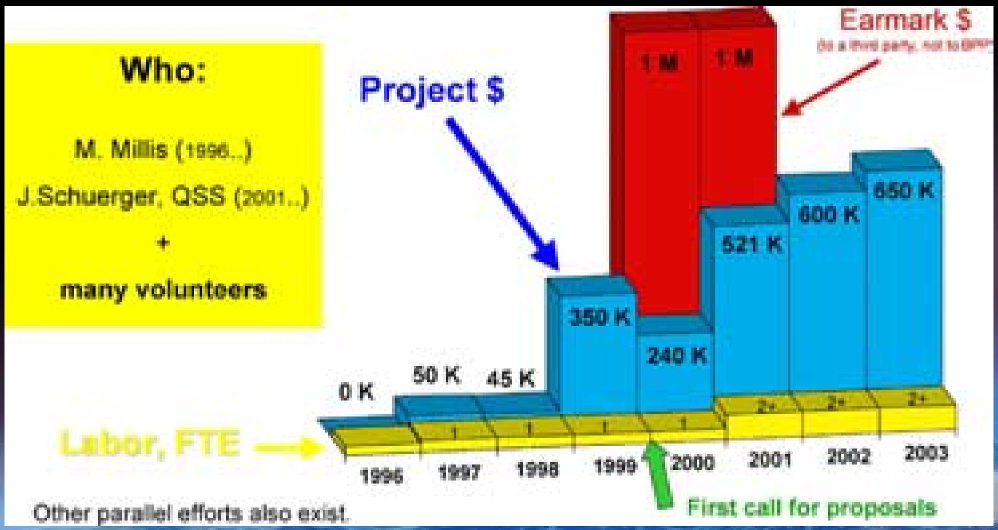
Implementation

Project Approach

- "Success" defined as **"acquiring reliable knowledge"** (rather than "achieving a breakthrough).
- Focus on ***immediate*** make-or-break issues, unknowns, or curious effects.
- Explore **multiple, divergent** research topics simultaneously.
- Sustain progress as a **series of** short-term, **incremental tasks.**
- Measure progress using the **scientific method.**
- Consider **visionary** specifications, yet tempered with **credible** methods and foundations **(reviews judge reliability of results, not feasibility of concept)**.

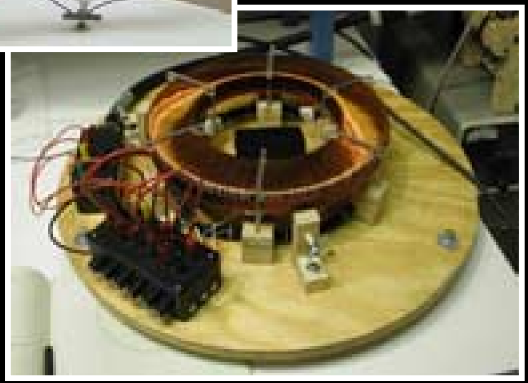


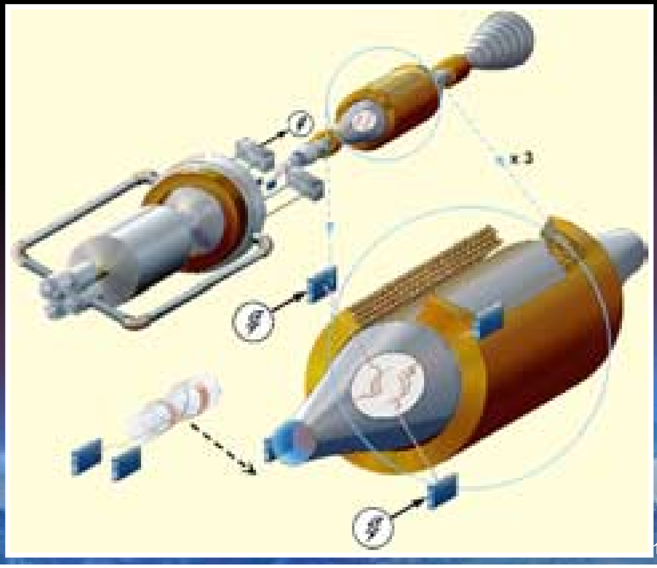
Budget / FTE



Summary of Investment Portfolio

- **Other**
  - Congressional Earmark to W. Virginia Institute for Software Research
    - Asymmetric Capacitor
      - experiments to date indicate that Trichel Pulses are part of the operation
    - Liquid Metal Flywheel
      - A generator mode has been built and demonstrated using a gallium-Indium eutectic
    - Fissioning Plasma Core Reactor Analysis
      - Analysis in support of INSPI/UF research
      - A significant number of core calculations have been run using U235 and Pu239
      - A kinetics code has been developed specifically for the analysis of the FPCR and preliminary results obtained





Funding Plans for FY03

- **Two NRAs, some basic support, and a few close out tasks continuing into FY03**
  - 60% for NRA for Revolutionary Propulsion Research and contract administration
  - 10% for NRA for Breakthrough Propulsion Physics and contract administration
  - 30% for NASA Centers basic support and completing critical experiments
    - GRC
      - Recombination Energy Fuels, needs one more year to get data from experiment
    - JPL
      - Li LFA thruster test facility completed, engine assembly underway, and testing will continue into 2003
      - Systems analyses and evaluation support
      - Database maintenance and Workshop Management
    - ARC
      - MHD accelerator tests and virtual inlet tests need to continue into 2003 somewhat.
    - MSFC
      - Antimatter trap experiment needs to travel to Fermi Lab to test filling
      - MHD accelerator tests with LyTec unit will continue into 2003 somewhat
      - Project Management support

Concluding Remarks

- Space transportation challenges are daunting but avenues of research exist which promise tremendous potential
- We must look beyond conventional technologies to ever make any real progress toward our ultimate goals

Scaling-up existing systems will never satisfy our ultimate desires

- Fundamentally, it is a problem of energy storage density and energy-to-thrust conversion efficiency – Energetics
- A comprehensive investment strategy has been developed which addresses the fundamental technical challenges while insuring scientific excellence and accountability to the customer
- This research strategy has been implemented over the course of several years with participation by NASA in-house staff, universities, government labs, and the private sector and has built a solid record of return on investment